Comparison of High-Frequency AC–DC Voltage Transfer Standards at NRC, VSL, PTB, and NIST

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***Abstract*—The paper summarizes results of two international comparisons relating thermal voltage converter (TVC) HF voltage standards of the National Research Council of Canada (NRC) to the standards of three National Metrology Institutes (NMIs): NMi Van Swinden Laboratorium (VSL), The Netherlands, Physikalisch-Technische Bundesanstalt (PTB), Germany, and National Institute of Standards and Technology (NIST), USA. The first comparison was part of the CCE 92-05 Intercomparison of AC–DC Voltage Transfer Standards at HF (1–50 MHz), [1]. The second comparison was carried out using a calorimetric thermal voltage converter (CTVC) of NRC design. Results of both comparisons show very good agreement in the frequency range (10 Hz–100 MHz) between NRC and the three other NMIs, thus validating the design of the NRC CTVC as a wideband reference standard of the ac–dc voltage transfer difference [2].**

***Index Terms*—AC–DC transfer, calibration, coaxial transmission lines, electric variables measurement, measurement standard, thermal converter.**

I. Introduction

During the last few years, a project was carried out at NRC to redesign and optimize the primary standard of HF ac–dc transfer difference (ac–dc difference), the calorimetric thermal voltage converter (CTVC). The design of the converter and its calculated frequency characteristic, which is practically flat over eight decades of frequency, 1 Hz–100 MHz, has been described previously, [2], [3]. In addition to calculable frequency characteristic, the CTVC has several other advantages. It is small, robust, not easily damaged, and very well suited for transport. It has a relatively long time constant, 15 s, which makes it more difficult to measure in comparison to regular vacuum-junction thermal voltage converters (TVCs), but this long time constant extends its frequency range to 1 Hz and below. The CTVC uncertainty evaluation, presented in [2], shows that in the frequency range 1 MHz–100 MHz it can be characterized more accurately than other HF ac–dc difference standards, [1]. However, the results published previously were either calculated theoretically or estimated from experiments on different realizations of the same design and required verification by independent means. The international comparisons with three leading NMIs, reported in this paper, were carried out to verify and validate the design of the NRC CTVC as a reference standard of ac–dc difference at frequencies up to 100 MHz. This verification is very important because low-voltage comparison of the HF ac–dc transfer difference in the voltage and frequency range covered by the CTVC has been designated by the Consultative Committee for Electricity and Magnetism as a key comparison (CCEM-K6c, 3 V, 1 MHz–50 MHz).

The paper summarizes results of two international comparisons relating TVC HF voltage standards of the National Research Council of Canada (NRC) to the standards of three National Metrology Institutes (NMIs): 1) NMi Van Swinden Laboratorium (VSL), The Netherlands; 2) Physikalisch-Technische Bundesanstalt (PTB), Germany; and 3) National Institute of Standards and Technology (NIST), USA. The first comparison, part of the CCE 92-05 Intercomparison of AC–DC Voltage Transfer Standards at High Frequencies (1–50 MHz), was carried out after the report [1] had been published. CCE92-05 was piloted by VSL and used a VSL designed standard. The second comparison, piloted by NRC, used the CTVC as the traveling standard and was conducted over the frequency band from 10 Hz to 100 MHz. Its additional goal was to test the CTVC as a possible traveling standard for future NORAMET or SIM comparisons.

II. NRC Participation in CCE 92-05 Intercomparison

During this comparison at the best accuracy, two traveling standards were used: 1) the VSL Calculable HF ac–dc transfer standard (TS-HF) and 2) a commercial converter, Fluke model A55, TS-A55. The TS-HF converter was a 5 mA, 4 V converter equipped with a type-N male input connector. The TS-A55 converter was a commercial 5 mA, 3 V converter with a GR874 input connector. Both converters were measured at NRC in September 1998. Fig. 1 shows the ac–dc difference of the TS-HF converter, as determined by VSL, the pilot laboratory, and NRC. The base value in Fig. 1 is the mean value of the comparison, as reported in [1]. Very good agreement between the two laboratories should be noted. At 100 MHz the difference in the measured ac–dc difference was less than 0.15 mV/V, significantly less than the combined uncertainty of the two laboratories (1.1 mV/V, $k = 1$). A similarly good agreement between VSL and NRC was achieved when TS-A55 was measured using an asymmetrical Tee (N/N/GR874) supplied by the pilot laboratory. However, NRC results obtained using a NRC asymmetrical Tee were significantly different from the VSL results, approximately 2.2 mV/V, which prompted investigation of the parameters of the asymmetrical Tees. These

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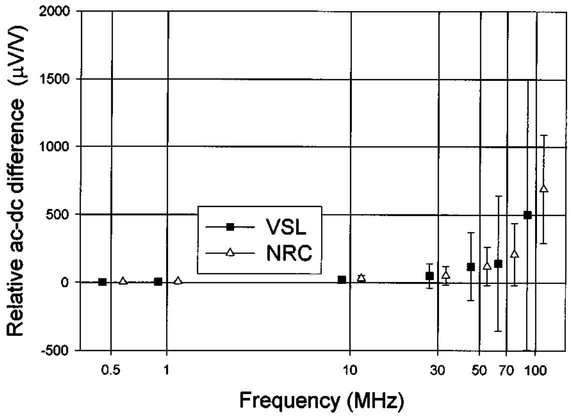

Fig. 1. Results of relative ac–dc transfer difference for the frequencies (0.5, 1, 10, 50, 100) MHz for TS-HF traveling standard. Uncertainty bars shown for $k = 1$.

tests, which will be reported separately, confirmed that the differences are due to the asymmetrical Tee design.

III. Comparison Using a CTVC Traveling Standard

A. CTVC Traveling Standard

The NRC calorimetric converter has been designed with an internal Tee, [2], [3]. One arm of the Tee, a short coaxial line, is terminated by a microwave rod resistor. Energy dissipated in this resistor raises its temperature above the temperature of the enclosure. The resistor temperature is measured by a 100-junction copper-constantan thermopile. To the other arm of the Tee is soldered the center pin of the type-N connector, used to attach the converter under test. The input test voltage is applied to a SMA-type connector connected to the center of the Tee by a copper plated stainless steel tube.

The CTVC is mechanically and electrically stable and not easily damaged by overloading. However, it is relatively more difficult to measure than a regular TVC due to its small output voltage, 4.5 mV at 1 V; long time constant, 15 s; and a close coupling of the cold junctions of the thermopile to the enclosure, which increases its sensitivity to the changes of the ambient temperature. The experience of this comparison has shown that it usually requires modifications in the ac–dc automatic comparator software and a close attention to a good thermal insulation from the ambient to obtain satisfactory results on the CTVC. Consequently, the standard deviations of typical tests were, in the range of a few microvolts per volt, much higher than in tests of a vacuum-junction thermal converter.

For the purpose of this comparison, a new CTVC, designated CTVC S/N 9817, was manufactured. It was measured at NRC during September 1998 and 1999, at VSL in November 1998, at PTB in June–August 1999 and at NIST in October–November 1999. At NRC, VSL, and PTB the traveling standard was measured at 1 and 2 V, at NIST at 1 V below 1 MHz and at 0.5 V above 1 MHz. All results were adjusted to 2 V. The frequency independent part of the ac–dc difference of the CTVC changed from 2 V to 1 V by approximately 1.2 μV/V.

B. References and Test Methods

In all four NMIs, the highest accuracy standards of the ac–dc difference are multijunction thermal converters [5], limited in frequency range to less than 10 kHz at NRC and NIST, 100 kHz at VSL, and 1 MHz at PTB. The HF ac–dc transfer standard is calibrated at LF by direct or indirect comparison with the MJTC. Each of the NMIs participating in the comparison derives its HF ac–dc difference standards independently and uses different techniques to determine their characteristics. These standards and methods are described briefly below in the order of NMIs participation in the comparison. The uncertainties associated with the comparison have been published previously in the referenced papers.

1) *National Research Council:* The highest accuracy standards of the ac–dc difference is a group of four MJTCs. The average ac–dc difference of this group is taken to be zero up to 10 kHz. Above 10 kHz NRC relies on the CTVC as the primary standard. The frequency characteristics of the CTVC are determined from theoretical computations. The LF current-dependent difference of the CTVC is determined by comparison with the MJTC at 1 kHz.
2) *NMi Van Swinden Laboratorium:* VSL relies on MJTCs in the frequency range 10 Hz–100 kHz. Above 100 kHz and up to 100 MHz, VSL uses a coaxial TVC amenable to modeling. It contains a serially connected range resistor, that consists of a very thin resistive wire, and a vacuum junction thermal element, mounted in cylindrical brass housing equipped with a type-N input connector, [4]. This design of the standard was characterized by modeling and verified by extensive comparative tests on structures with different parameters. The CTVC was compared directly to both VSL standards, the MJTC and the calculable standard.
3) *Physikalisch-Technische Bundesanstalt:* The primary PTB standards in the frequency range 10 Hz–1 MHz are MJTCs [5]. At higher frequencies, the PTB HF-DC voltage transfer standard is a dc-coupled 50 Ω RF resistance mount with a known effective efficiency η_{eff} and an input admittance $Y(f) = G(f) + jB(f)$. For frequencies below 50 MHz, values for η_{eff} and G were determined by modeling of the mount and extrapolating the HF values to lower frequencies. The HF values of the resistance mount were determined from a comparison with a coaxial bolometer mount which was calibrated in the PTB microcalorimeter [6]. Below 1 MHz, the traveling standard was compared to a PTB MJTC. Above 1 MHz, it was compared to the PTB resistance mount, in an ac–ac mode, i.e., the characteristic of the CTVC was referenced to the lowest frequency of the range, 1 MHz, rather than to dc. The ac–ac transfer difference of the working standard, referred to 1 MHz, is given by

$$\delta_{\text{ac–ac}}(f) = \sqrt{\left(\frac{1}{\eta_{\mathrm{eff}}(f)}\right)} \cdot \sqrt{\frac{G(\mathrm{f_{ref}})}{G(\mathrm{f})}} - 1 \qquad (1)$$

where $G(f_{\mathrm{ref}})$ is the input conductance calibrated at reference frequency of 1 MHz. The ac–dc difference $\delta_{\mathrm{ac-dc}}$ can be calculated from the LF calibration at $f_{\mathrm{ref}} = 1$ MHz as

$$\delta_{\mathrm{ac-dc}}(f) = \delta_{\mathrm{ac-dc}}(f_{\mathrm{ref}}) + \delta_{\mathrm{ac-ac}}(f) \tag{2}$$

for $|\delta_{\mathrm{ac-dc}}(f_{\mathrm{ref}})| < 100\,\mu$V/V and $|\delta_{\mathrm{ac-ac}}(f)| < 10$mV/V.

4) *National Institute of Standards and Technology:* Up to 1 MHz, NIST ac–dc differences of coaxial thermal converters are characterized using LF standards, MJTCs, and set of converters with different range resistors with nearly frequency independent structures [7]. The traveling standard was compared to such a characterized working standard. Above 1 MHz, the NIST wideband sampling voltmeter (WSV) was used. The frequency response of the WSV, described in [8], was determined by applying a fast step input signal, taking the first forward difference of the acquired step data (to get the WSV impulse response), and then taking the FFT of the impulse response. This technique is fully described in [9]. The corrected WSV was then compared to the CTVC in an ac–ac mode, as at PTB, using 100 kHz as the reference frequency. A PID software servo was used to keep the CTVC output emf constant for each applied frequency. The resulting comparison data was calculated using the following formula:

$$\delta_{\mathrm{ac-ac}}(f) = \frac{W(f) - W(f_{\mathrm{ref}})}{W(f_{\mathrm{ref}})} \tag{3}$$

where $\delta_{\mathrm{ac-ac}}(f)$ is the calculated ac–ac difference between the WSV reading at the applied frequency, $W(f)$, and the WSV reading at the reference frequency, $W(f_{\mathrm{ref}})$, $f_{\mathrm{ref}} = 100$ kHz. The ac–dc difference was then calculated using (2).

IV. Test Results

The results of tests of the traveling standard are shown in Figs. 2 and 3. Fig. 2 shows results of measurements of the CTVC S/N 9817 in the frequency range 10 Hz–1 MHz, conducted using more accurate, LF ac–dc difference reference standards and comparators. Results are presented as the difference between the NMI reported value and the average of all four results. These results mirror results of comparison CCE 92-3, [5], conducted in 1994–1996 by PTB. It should be added that the new comparison was carried out also at (10, 20, 40, 100) Hz, frequencies not covered in [5]. Almost all expanded uncertainties overlap. Only at 300 kHz there appears to be a small but statistically significant difference between NRC and PTB, requiring further examination. The uncertainty of these tests is larger than during comparison reported in [5] due to two factors. The first was a large time constant of the CTVC and the second was noise introduced by an insufficient insulation of the CTVC thermopile from the temperature variation of the ambient.

Fig. 3 shows test results for frequencies 1 MHz–100 MHz. Here, the results are presented as relative to the average of three laboratories: NRC, VSL, and PTB, because of the relatively large uncertainties quoted for the NIST-WSV results

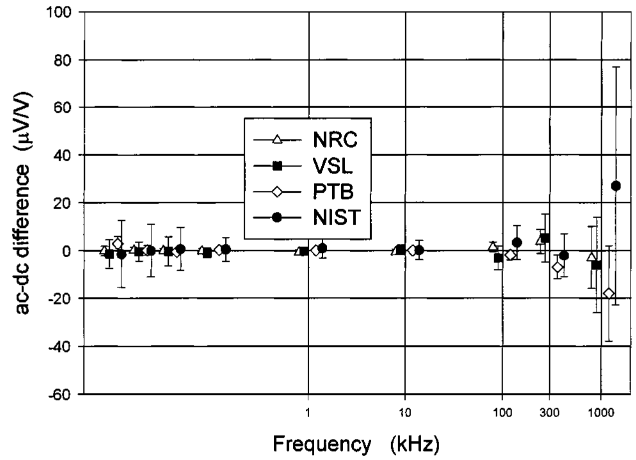

Fig. 2. Results of relative ac–dc transfer difference for the frequencies (0.01, 0.02, 0.04, 0.1, 1, 10, 100, 300, 1000) kHz for CTVC traveling standard. Uncertainty bars shown for $k = 2$.

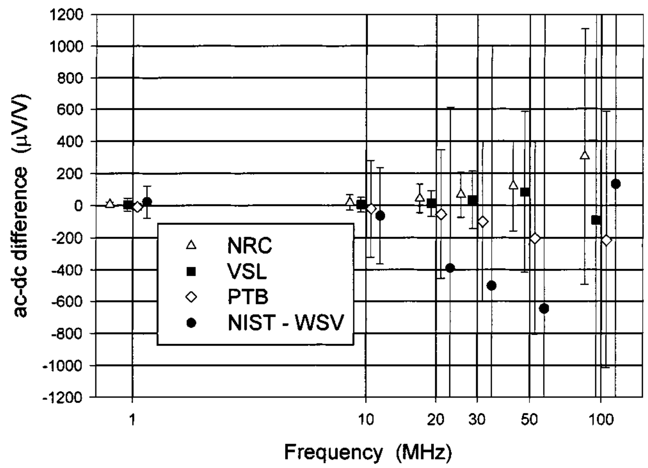

Fig. 3. Results of relative ac–dc transfer difference for the frequencies (1, 10, 20, 30, 50, 100) MHz for CTVC traveling standard. Uncertainty bars shown for $k = 2$. NIST data for WSV.

[(0.1, 0.3, 3) mV/V at (1, 10, 100) MHz, $k = 2$]. These large uncertainties are associated with the calibration of the WSV using a fast step input signal. The WSV and the step generator used to calibrate it have been designed using SMA connectors, and an SMA to type-N adapter was necessary to connect the WSV to the CTVC. This adapter contributes a large source of error for the WSV results. The results obtained during this comparison are very promising and indicate that in the tested frequency range the WSV is capable of performance comparable to TVC and CTVC standards.

The results of NRC, VSL, and PTB agree very well. The results of NIST WSV are much closer to the results of the remaining laboratories than the quoted uncertainty would indicate. At higher frequencies, the noise introduced by the CTVC bears almost no influence on the final uncertainty which is determined mostly by a much larger uncertainty of a primary standard.

The flat frequency characteristic of the CTVC proved to be very advantageous during tests and adjustments of the WSV.

V. Conclusions

The comparisons presented in the paper show very good agreement between the NRC standard, the CTVC, and the VSL, PTB, and NIST ac–dc transfer difference standards, in the whole frequency band 10 Hz–100 MHz. This agreement confirmed and validated the CTVC uncertainty evaluations. The experience in using the CTVC as the traveling standard showed its very good stability, repeatability, and insensitivity to overloading. However, its outer enclosure should be redesigned to better insulate the active part of the CTVC from the ambient. The experiments with the WSV indicated that CTVC could find application in calibrating such instruments.

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